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Understanding climate policy projections: A scoping review of energy-economy models in Canada

Ekaterina Rhodes [a,*], Aaron Hoyle [b], Madeleine McPherson [c], Kira Craig [d]

[a] School of Public Administration, University of Victoria, PO Box 1700 STN CSC, Victoria, BC, V8W 2Y2, Canada
[b] Energy and Materials Research Group, Simon Fraser University, 8888 University Dr., Burnaby, BC, V5A 1S6 Canada
[c] Sustainable Energy Systems Integration and Transitions Group, University of Victoria, PO Box 1700 STN CSC, Victoria, BC, V8W 2Y2 Canada
[d] School of Public Administration, University of Victoria, PO Box 1700 STN CSC, Victoria, BC, V8W 2Y2, Canada

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ABSTRACT

Energy-economy models play an increasingly important role in informing climate policy decisions, yet their results lack consistency in terms of projected greenhouse gas emissions and economic impacts. The paper employs a scoping review of the key improvements, knowledge gaps, and critiques of energy-economy models in the academic, public, private, and not-for-profit sectors in Canada over the past ten years. The three objectives are to (1) identify the key energy-economy modelling assessment criteria, (2) develop an inventory of energy-economy models assessed against the criteria in objective 1, and (3) discuss implications for modelling climate policies. Four criteria for assessing the ability of energy-economy models to evaluate climate policy impacts are identified: treatment of technology, microeconomic realism, macroeconomic realism, and policy representation. The assessment of 21 models against these criteria reveals similarities and differences across models. Models that share similarities in over-arching methodological approaches are also similar in the way they represent technologies, market heterogeneity, trade effects, different policy types, and energy equilibrium. Conversely, there are quite diverse approaches used in the representation of technological change, non-financial decision factors, financial or monetary features, and non-energy equilibrium. Model documentation does not often address how policy interaction is taken into account. Based on this assessment, implications for climate policy modelling and future research are discussed.

1. Introduction

As part of the global Paris Agreement, 189 nations pledged to reduce greenhouse gas (GHG) emissions to ensure the global average temperature does not exceed 2 °C [1]. Canada set a GHG emissions reduction target of 40–45% by 2030 below 2005 levels and net zero by 2050 [2]. To achieve these targets, the federal and many provincial and territorial governments implemented a variety of climate policies, including carbon pricing, sector-specific regulations, incentives for clean technologies, and low-carbon infrastructure investments. However, forecasted impacts of these policies across different energy-economy models vary dramatically in terms of GHG and economic outcomes [3–5]. For example, using an in-house energy-economy model, E3MC, Environment and Climate Change Canada [4] projects that national GHG emissions could decrease by 15% below 2005 levels by 2030 under current climate policy at the time of the analysis. Using different models with similar policy assumptions, Jaccard et al. [5] and Bataille et al. [6] find that national emissions are likely to fall by 8–9% below 2005 levels by 2030. The discrepancy in modelling results highlights the need to better understand differences in modelling methodologies and their implications for climate policy projections.

Quantitative models of the energy-economy are widely used to understand and determine policy responses to climate change in the energy sector. Models are often applied to global energy system analysis, in addition to individual nations or sub-national regions (e.g., provinces and territories) to form an evidence base for climate policy analysis. Given the complexity and diversity of energy-economy models (also termed "energy-environment-economy" models), designed for a variety of purposes, this review aims to help researchers and decision-makers to understand why (or why not) a particular energy-economy model might be well positioned to answer their research and policy questions.

Over the past decade there have been increasingly disparate attempts to improve climate policy projections in energy-economy models. Some

* Corresponding author.
E-mail addresses: krhodes@uvic.ca (E. Rhodes), aaron_hoyle@sfu.ca (A. Hoyle), mmcpherson@uvic.ca (M. McPherson), kbcraig@uvic.ca (K. Craig).

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Abbreviations:

BAU	business-as-usual
CGE	computable general equilibrium
GHG	greenhouse gas
N/A	not available

of this work exists in academic literature [7–10], while the rest occurs in private and not-for-profit sectors with limited access to methodological information [11–13]. There are also debates about the key modelling characteristics that help produce 'more realistic' climate policy forecasts [14,15]. In fact, most model review studies do not conduct literature searches to identify the most cited model assessment criteria important for producing GHG and economic projections under climate policy. Furthermore, information about existing modelling tools, recent improvements, or their criticisms is not consistently summarized in a publicly accessible manner. Some of the published reviews focus exclusively on energy systems models (rather than energy-economy models) without incorporating economic agent behaviour and using different assessment criteria and model classification schemes.

The study develops a scoping review and discussion of the key improvements, knowledge gaps, and critiques of energy-economy models that have so far been used in the academic, public, private, and not-for-profit sectors in Canada over the past decade. The key objectives of the review are as follows:

1. Identify the key energy-economy modelling assessment criteria,
2. Develop an inventory of energy-economy models assessed against the criteria in objective 1, and
3. Discuss implications of model assessments from objective 2 for climate policy modelling.

The study is organized as follows. Section 2 reviews the key typologies of energy-economy models. Section 3 describes the methodology of the scoping review. Section 4 summarizes results of the review in regards to the model assessment criteria (objective 1) and how energy-economy models in Canada score against these criteria (objective 2). Section 5 discusses implications for modelling climate policy (objective 3). Section 6 summarizes the key findings and outlines opportunities for future research.

2. Model typology

Most energy-economy models can be grouped into three main categories: bottom-up, top-down, and hybrid depending on the degree of incorporating methodological characteristics of technological explicitness, behavioural realism (microeconomic realism), and equilibrium (macroeconomic) feedbacks [16–18]. This categorisation is not exhaustive or prescriptive as some models may not ideally fit within a particular category; for example, some integrated assessment models can belong to any of the three categories depending on their design. However, many studies have suggested that, for comparative purposes, it is pedagogically appropriate to categorize models this way [17–21]. Therefore, the paper adopts this model typology to identify descriptive features of the models that have similarities according to the approximate category they appear to belong to.

Technological explicitness is the level of detail to which current and emerging technologies are represented in a model [22]. The level of behavioural realism depends on whether human preferences are accounted for, including intangible costs, or if decisions are only based on minimizing costs [17]. Equilibrium feedbacks are how the equilibrium of prices, demand, and supply level of goods in the macroeconomy are affected by a policy [23].

The main strength of bottom-up models is their high level of technological explicitness. Current and future technologies are characterized in detail including their market shares, capital and operating costs, emissions profile and energy use [17,19]. A criticism of bottom-up models is their lack of behavioural realism because they assume different technologies are perfect substitutes and that financial costs are the only factor in the estimate of social costs of technological change [17]. This is not an accurate depiction of reality as other behavioural (intangible) costs are included in technology purchasing decisions such as consumer preference, higher chance of premature failure, and differing financial costs between consumers [16]. However, emerging research suggests that some bottom-up models are starting to incorporate some of these microeconomic costs recognizing the importance to account for realistic behavioural preferences [24]. In addition, such models do not consider macroeconomic feedbacks, since energy sector technologies are not interacting with the rest of the economy [25]. As a result, bottom-up models underestimate the total cost of emissions abatement, which leads to overly optimistic GHG reductions under climate policy [26]. The high level of technological detail makes bottom-up models useful when policy-makers are trying to determine the potential impacts of emissions from future technologies and energy demands [27], as well as the showing the technological possibilities to meet environmental targets [16].

In contrast, top-down models take an aggregated approach by focusing on the interactions between the energy system and the rest of the economy [20]. Top-down models, such as computable general equilibrium (CGE) models, can assess the links between sectors to determine how a policy directly impacts the rest of the economy through macroeconomic equilibrium feedbacks [23]. Top-down models are also able to incorporate behavioural realism as the parameters used for projections are based on historical data so they contain the intangible behavioural costs consumers and businesses include in making technological purchasing decisions [17]. The problem with the use of historical data is decision-making of the past may not be indicative of future decisions, especially for newly emerging behaviours [17,19]. By focusing on the overall processes in the economy at a simplified level compared to bottom-up models, top-down models lack technological explicitness and neglect to account for technology preferences. The combination of these factors contributes to an overestimation in emissions abatement costs [28]. Top-down models are useful when modelling large scale policies such as taxes, but the absence of technological detail means they are inadequate at modelling technology specific polices such as subsidies [26].

To overcome the challenges faced by bottom-up and top-down models, hybrid energy-economy models were developed. Hybrid models combine the strengths of top-down (equilibrium feedbacks and behavioural realism) and bottom-up (technological explicitness) models. This hybridization can be done through the addition of technological explicitness into a top-down model or incorporating behavioural realism and/or equilibrium feedbacks into a bottom-up model [17]. The application of a hybrid framework to a policy scenario typically results in more modest GHG reductions due to the inclusion of intangible non-financial costs compared to a bottom-up methodology [10].

In addition to top-down, bottom-up, and hybrid models, system dynamics models (e.g., production cost, capacity expansion), and integrated assessment models are also used for the assessment of climate policies. These models are treated as a separate type from top-down, bottom-up, and hybrid categorisations in the analysis and results. System dynamics models are similar in their analytical approach to bottom-up models, including in their accounting of fuels, technologies, and intermediate energy flows, and calibration to historical data. However, there are consequential differences. Instead of simulating the evolution of an economy's energy system using empirically estimated parameters, many system dynamics models employ deterministic assumptions about flows of energy, and stocks of energy-related technologies. Integrated assessment models aim to link the dynamics of a region's energy-economy with those of the biosphere and atmosphere. The detail and extent to which models represent diverse systems vary widely, but all represent economic processes and activities that produce GHG emissions to some degree [29,30].

3. Methodology

A scoping review was conducted to address the study's objectives. Scoping reviews synthesize the key concepts behind a research topic, including the main sources, available evidence, and knowledge gaps, making them especially useful where a topic is complex or has not been researched comprehensively [31]. Given the extent and complexity of the topic of climate policy modelling, as well as the lack of synthesis literature focusing exclusively on energy-economy models, the study uses a scoping review method with pre-defined inclusion criteria (see below).

Although the terminology surrounding climate policy modelling can be varied, researchers' explanations of what constitutes an energy-economy model are generally consistent [15,18,19,32]. "Energy-economy models" are defined in this study as those that examine the linkages between all energy sectors and the economy of a region. Thus, models that focus only on a particular feature of the energy system are excluded in the review (e.g., production cost, capacity expansion models).

To identify model assessment criteria against which to compare energy-economy models (objective 1) a narrative review method was employed, which synthesized peer-reviewed literature familiar to the authors [33]. Several recent energy-systems reviews offered a useful starting point, in particular Lopion et al. [29] and Savvidis et al. [30]. However, the criteria used in recent reviews are quite diverse, and not constrained to energy-economy models; this study applies a tighter scope of criteria.

Using the ScienceDirect and Google Scholar electronic databases, potential literature was identified using the following search string: ("energy-economy model" OR "energy-environment-economy model" OR "E3 model") AND ("review" OR "criteria" OR "assessment" OR "evaluation"). "Climate-economy" and "integrated assessment" keywords were excluded from the criteria search string due to the scope of the study to compare models against energy-economy characteristics, rather than climate science-related features. The search returned 3,982 publications across both databases. This literature was scanned for suggestions on how to improve the evaluation of GHG and economic outcomes of climate policies using energy-economy models. The aim was to uncover nuances and themes in the literature (e.g., trade-offs in analytical approaches). Next, reference lists, particularly of recent articles and reviews, were used to lead to other useful papers. Authors or research groups that were frequently mentioned were identified, and their peer-reviewed publications were scanned for suggestions potentially relevant to criteria identification. However, these lists were not comprehensive nor exhaustive, thus not intended as a scoping review to identify all criteria used for model categorizations.

To develop an inventory of energy-economy models (objective 2), academic peer-reviewed literature and public reports from public, private, and not-for-profit organizations were reviewed to develop a list of energy-economy models used across Canada. Then these models were described against the identified modelling assessment criteria in objective 1.

Energy-economy models were considered eligible for inclusion based on their ability to evaluate economy-wide climate policies: if they were used to assess GHG and economic impacts of climate policies in Canada between 2009 and 2019 (inclusive); and if there was sufficient publicly available documentation to evaluate the model against the criteria discussed above. Models were identified via ScienceDirect and Google Scholar databases in June 2020. The following search string was used: ("energy-economy model" OR "energy-environment-economy model" OR "integrated assessment model" OR "E3 model") AND ("Canada" OR "British Columbia" OR "Alberta" OR "Saskatchewan" OR "Manitoba" OR "Ontario" OR "Quebec" OR "New Brunswick" OR "Nova Scotia" OR "Newfoundland" OR "Prince Edward Island" OR "Northwest Territories" OR "Yukon" OR "Nunavut"). "Integrated assessment model" and "E3 model" terms were included in this search string to solely assess and compare energy and economy characteristics of the models without examining their climate science-related characteristics, as per the criteria search string above. This search method returned a total of 961 results. Of this initial sample, duplicates and papers that were not used to assess GHG and economic impacts of climate policies in Canada were removed. The product was 54 publications, which included peer-reviewed articles and 'grey' literature (e.g., theses or government reports). These publications identified 21 unique models. The study's focus on models used in Canada potentially limits the comprehensiveness of the review for the entire energy-economy modelling ecosystem worldwide, but provides useful insights for at least Canadian climate policy-makers, practitioners, and academics who use and/or develop the reviewed models.

Next, models were compared against assessment criteria qualitatively. The evaluation was based on answering guiding questions—some binary, some open-ended (see Table 2). The guiding questions were based on the literature supporting the model assessment criteria. Answers were formed using publicly available information on the model in question. For some binary responses, further qualitative explanations were added if sufficient information was available. Information that was not available with respect to certain criteria is indicated in the analysis.

4. Results

4.1. Assessment criteria

The literature search identified the following four most cited criteria and sub-criteria (given in parentheses): (1) treatment of technology (explicit representation, technological change) found in 22 articles; (2) microeconomic realism (market heterogeneity, non-financial decision factors) found in 21 articles; (3) macroeconomic realism (energy equilibrium, non-energy equilibrium, trade and finance) found in 10 articles; and (4) policy representation (policy types, policy interaction) found in 5 articles. In particular, the following recent model criteria reviews (or review sections of studies) were compared to inform the selection of assessment criteria (discussed in further detail in Sections 4.1.1-4.1.4 below): Clarke et al. [34], Lopion et al. [29], Savvidis et al. [30], Prina et al. [35], Li et al. [36] and Mercure et al. [37] for the treatment of technology; Mercure et al. [37], Clarke et al. [34], Li et al. [36] and Li et al. [38], for microeconomic realism; Hall et al. [39], Savvidis et al. [30], Mercure et al. [37], Hedenus et al. [15], Clarke et al. [34], and Goulder & Parry [40] for macroeconomic realism; Goulder & Parry [40], Savvidis et al. [30], and Bhattacharyya & Timilsina [41] for policy representation.

Many model assessment criteria could have been used in addition to these four, but were excluded from the review of models. Three alternative criteria in particular are commonly discussed. First, many modelling studies and their reviewers emphasize the need for transparency in energy-economy modelling methods and data management [e.g., 19,28], and associated replicability of modelling studies [42–44]. Second, the treatment of uncertainty is commonly used as a criterion in existing energy-systems modelling reviews [15]. Finally, Lopion et al. [29], Pfenninger et al. [44], and Savvidis et al. [30] point out the need to include a high-resolution representation of time and space in order to simulate renewable energy supply, especially for electricity generation [45,46].

While other criteria could have been used in the model review, the four criteria below were chosen because (a) they determine to a greater extent the ability of energy-economy models to predict GHG and economic impacts of climate policies relative to the alternatives, as per the accessed literature, and (b) other criteria were not as consistently highlighted in the literature.

4.1.1. Treatment of technology

Treatment of technology refers to the level of resolution at which a model represents technological information and how technological dynamics are captured. The development and deployment of technology is crucial to long-term climate change mitigation because the established fossil fuel-based energy supply will need to be replaced with low-carbon alternatives [34]. It follows that the treatment of technology by energy-economy models is crucial to the assessment of climate policies.

There are two primary interdependent attributes that energy-economy models rely on to assess economic outcomes and GHG emissions as related to the treatment of technology: the extent to which a given model explicitly represents technology, and how the model represents the evolution of the capital stock of energy-related technologies within the economy (i.e., technological change).

4.1.1.1. Explicit representation. Explicitly representing technologies, often characterized in terms of capital and operating costs, fuel consumption, and emissions profiles, increases the usefulness of models to policy-makers [17,47]. Financial costs are usually converted into a present value using a discount rate that represents the opportunity cost of capital [18]. Assessment of the effects of climate policies on GHG emissions, abatement costs, and other economic outcomes are heavily influenced by the availability, cost, and performance of mitigation technologies. Modelling studies indicate that as the stringency of climate policies increase, so does the influence that technology parameters have on the results [34]. Explicit representation allows for the use of empirically-based technology-level data, such as costs, availability, energy efficiency, and fuel compatibility. Models that are more technologically explicit require more data, parameterization, and flexibility to update fast-evolving techno-economic characteristics that may drive heterogeneity in model projections [19,48,49].

There is strong support for the explicit representation of technologies as a desirable feature in the energy-economy modelling literature, especially in "bottom-up" energy-systems model reviews [e.g., 27,39]. For example, Savvidis et al. [30] include a "detail of modeling" criterion to assess the ability of models to answer policy questions. Similarly, Li et al. [36] conclude that when technologies are represented in adequate detail, the evidence base for policy interventions is strengthened significantly. Furthermore, they suggest that models should at the least include "[a] disaggregated portfolio of technology options with different price and performance characteristics" (p. 292). Finally, explicitly representing technologies allows models to capture technological change dynamics, which is especially important for emerging and near-commercial technologies [21,50].

4.1.1.2. Technological change. The methods used to represent technological change in energy-economy models are crucial to determining their results, such as GHG emissions, market outcomes, and abatement costs [19,25,51–55]. However, models are diverse in their representation of technological change, lacking consensus on the most optimal methods [34].

Energy-economy models representation of technological change can be categorized into two groups: exogenously, meaning that they treat it independently of policy measures, or endogenously, meaning through "induced technological change" [19,34,51]. With exogenous technological change, production possibilities depend only on time; with endogenous technological change, possibilities can depend on a variety of variables such as energy prices and cumulative production [51].

Exogenous technological change has been incorporated in energy-economy models using several methods. Some models include an "autonomous energy-efficiency improvement" parameter, which increases the energy efficiency of the economy each year [56]. A similar approach can be taken in more disaggregated models by assuming certain sectors or technologies become more energy-efficient over time [51]. Backstop technologies can also be added to models, often at a relatively high marginal cost, as a form of exogenous technological change if supply is specified to be virtually unlimited [25].

Endogenous technological change acknowledges that technological change does not depend just on time and current prices, but instead integrates feedback mechanisms by which policy influences the direction of technological change. Common endogenous technological change feedbacks have incorporated dynamic energy prices, representation of research and development, and lowering production costs through accumulated experience, known as "learning-by-doing" [25,51].

There is an ongoing debate on how to improve the treatment of endogenous technological change [36,37,57]. Gillingham et al. [51] suggest that some methods of endogenizing technological change appear better suited to certain model types than others. Methods based on research and design have been used more commonly in top-down models, while "learning-by-doing" methods have been used more commonly in bottom-up and hybrid models where technologies are represented explicitly [51,58].

The restricted treatment of technological change in some energy-economy models derives from limitations in the technical ability to represent the complexity of the subject, in addition to a lack of empirical evidence on its effects [59], but some modellers attempted to incorporate empirical data on technological change [34,60].

4.1.2. Microeconomic realism

Energy-economy models typically do not represent individual decision-makers, but rather "economic agents" that represent aggregate behavior. Microeconomic realism refers to the ability of a model to realistically represent agent behavior within the energy-economy, including the heterogeneity of consumer preferences, and non-financial decision factors. Integrating microeconomic realism helps ground the model in technology acquisition and use data.

Energy-economy models typically represent "rational" agent behavior through simplified economic relationships (e.g., investment as a function of levelized costs). Bottom-up models commonly use discount rates as a proxy measure of many different behavioral features [57]. In contrast, simulation models typically use logit functions, calibrated to empirical data, to represent heterogeneity through technology market shares [57]. Finally, in top-down models, behavioural features are often captured implicitly in parameter estimation (e.g., income or price elasticities) [37].

Many emphasize the importance of representing agent behavior in energy-economy models used for climate policy analysis [18,22,34,37,38]. Behaviorally-realistic modelling studies have shown that behavioral assumptions are important to assessing policy-relevant topics in the energy-economy [17,57]. These modelling results are based on empirically-derived parameters, supported by evidence on the behavioral influences on energy use and technology adoption [28,47,61,62].

There are a wide variety of factors that can determine agent behavior within the energy-economy. McCollum et al. [57] synthesize diverse literatures on behaviour and decision-making into four types of behavioral "features:" heterogeneity; individual (e.g., non-optimizing heuristics and non monetary preferences); social (e.g., neighborhood effects); and contextual (e.g., institutions shaping decisions and behavior through social norms). In addition, Gillingham et al. [63] review economic concepts underlying behavioral features in relation to energy use, and find that there is extensive evidence for real-world decision-making to deviate from "rational choice" models–agents are loss-averse, respond asymmetrically to economic costs and benefit, find and process information imperfectly and inefficiently, and use non-optimizing heuristic devices (e.g., habits) to make decisions.

The literature details two prescriptions of how to address microeconomic realism in energy-economy models: represent market heterogeneity, or integrate non-financial cost preferences. Market heterogeneity refers to variation of differences between energy consumers and/or producers such that not all decision-makers make the same decisions given similar circumstances [61]. Mercure et al. [37] and Li et al. [36] suggest that accurately forecasting the impacts of climate policies require models to include representation of the diversity of human behavior. Integrating market heterogeneity is especially important for analyzing technology market shares and production pathways. The reason is that if market heterogeneity is not represented, one technology may capture all of the market share–a dynamic referred to by some as "penny-switching" [16]. This model dynamic can be problematic when assessing climate policy because it does not allow for a variety of GHG abatement pathways and technologies to be used.

Second, behaviorally realistic models should represent non-financial costs [18,19,22,47], including the ability to assess how increasing market shares of technologies might affect future non-financial ("intangible") costs of acquiring technologies [19,47,64,65]. Some models rely only on financial costs evaluated at a social discount rate to calculate life-cycle costs, thereby ignoring differences of risk and quality between competing technologies. Models that include only financial costs can produce results that do not align with real-world firm and consumer decision-making, and can underestimate the costs of GHG abatement [10,57]. Ex-post modeling studies have also shown that relying solely on financial cost optimization does not accurately estimate real-world energy system transitions [[66]].

In particular, energy efficiency investment studies highlight the importance of including non-financial costs. Mundaca et al. [22] find that in addition to capital and operating costs, social and psychological factors determine technology choice. Murphy & Jaccard [10] explore the gap between perceived economic benefits of energy efficiency and actual consumer behavior that appears to ignore 'profitable' investments. This consumer behavior has been attributed to perceived unreliability of new technologies, and/or lack of information [34].

Researchers have used a variety of methods to estimate parameters for representing microeconomic realities, including calibration against historic data, stated or revealed preference data, and expert judgement. Behavioral model parameters have also been estimated through statistical simulations [67]. In particular, discrete choice surveys help support models that aim to convert qualitative knowledge about agent behaviour into quantitative parameters [22,26].

In addition to individual behavior, social preferences and institutional structures can influence the use of technologies and determine, to some extent, the impacts of climate policies [34]. However, very few models incorporate such elements, precipitating research that is often not included in climate policy analysis [68,69].

4.1.3. Macroeconomic realism

Macroeconomic realism refers to the ability of a model to represent the structural systematic relationships of a region's economy. In particular, a model that has a high degree of macroeconomic realism includes feedbacks such as trade, financing, and links between energy supply-demand and an economy's structure and output.

Because climate policies are likely to yield both economic benefits and costs, it is crucial to policy-makers to determine what impact climate policies might have on the economy [37]. Thus, models are more useful to policy-makers if they include equilibrium feedbacks that link production costs of goods and services to their supply and demand, in addition to general economic feedbacks (e.g., the balancing of government budget and labor, and investment markets) [18,19,47]. Hall & Buckley [39] and Savvidis et al. [30] include macroeconomic realism in their model categorizations, albeit using somewhat different terminology such as "energy sectoral coverage" and "demand representation."

Models that represent the economy of a region and the degree of interaction across sectors do so with differing degrees of detail and methods, which can be categorized into two common approaches. First, general equilibrium methods link economic feedbacks in a full equilibrium framework. They are used to estimate aggregate relationships between the relative costs and markets shares of energy and other inputs to the economy, and link these estimates to sectoral and economic output [15]. Partial equilibrium methods partially link major equilibrium feedbacks, often focusing on key systems such as the energy sectors of an economy [34]. In either case, a common approach is to represent energy supply-demand by linking all energy-consuming sectors of the economy to energy-producing sectors of the economy. Energy prices and quantities are solved for, such that equilibrium is achieved between supply and demand for each energy source across all sectors. Besides full and partial equilibrium methods, other less common approaches include macroeconometric non-equilibrium methods that do not require market clearance, which can be useful in the short term.

Models also differ in terms of representing the flow of goods across regions. Some models assume that goods are homogenous, while others assume a preference for domestic over imported goods [34]. Most general equilibrium energy-economy models rely on an Armington [70] structure of international trade, but research has suggested that empirical evidence supports alternative theories of how trade and border adjustments interact with climate policy [71].

In addition, Mercure et al. [37] emphasize that representing the monetary and financial sectors is crucial in models used for exploring the economic impacts of climate policies. The differences between model's treatment of innovation, money, and finance reflect a lack of consensus between economics and social scientists. Improving model representations of monetary and finance dimensions, and their interactions with investment, innovation and technological change, allows researchers to gain a more consistent picture of the macroeconomic impacts of climate policies [37].

4.1.4. Policy representation

Policy representation refers to the ability of a model to accurately represent different types of climate policies, whether implemented individually or in combination with each other. These can include versions of carbon pricing, prescriptive regulations, performance standards, and government investment and subsidies [40]. Carbon pricing, either as a direct tax or a cap-and-trade system, captures the external costs of carbon emissions by attaching a price to the fossil fuels according to their carbon content. "Command-and-control" regulations generally prescribe the nature of GHG abatement within an industry. Performance standards or "flexible" regulations mandate an outcome through market-based mechanisms, but not the means by which to achieve emissions reductions [72]. Government investment and subsidies are non-compulsory measures that aim to reduce emissions through lowering financial or non-financial costs of technologies or via internal management practices.

The literature supports the inclusion of policy representation, but less so than for the treatment of technology, microeconomic realism, and macroeconomic realism [30,41]. Recent studies have highlighted the importance of carefully considering policy interaction in quantitative assessments of climate policies [[73]]. The ability of energy-economy models to represent different types of policies depends in large part on their analytical approach, intertwining policy representation and the other three criteria summarized above. For example, to accurately represent a technology-specific regulation, a model should explicitly represent that technology.

4.2. Model assessment

Table 1 summarizes the 21 models that qualified according to the search criteria. The most recent model versions that had publicly available documentation were reviewed. Due to ongoing development, most of the models and their classifications are subject to continuous modifications, which are not always documented. The presented models descriptions and classifications should not be treated as ultimate or prescriptive—they are only used here to describe general

Table 1
Energy-economy model descriptions.

Model	Version	Examples of source(s)	Developer(s)	Description	Jurisdictional application	Example(s) of model user (s)
CIMS	2017	Jaccard [19], Rivers & Jaccard [17]	Navius Research/Simon Fraser University	Hybrid (bottom-up, partial equilibrium)	National, sub-national, and regional	Navius Research, Simon Fraser University
Canada Energy Policy Simulator	V1.1.4	Energy Innovation LLC [74]	Energy Innovation LLC	System dynamics (capital stock turnover)	National, sub-national, regional, and municipal	Pembina Institute
CanESS	2020	whatif? Technologies Inc. [75]	whatIf? Technologies Inc.	System dynamics (bottom-up, capital stock turnover)	National and sub-national	Canadian Energy Systems Analysis Research
CIMS-Urban	2018	Jaccard et al. [7]	Simon Fraser University	Hybrid integrated with urban land-use (bottom-up, partial equilibrium)	Municipal	Simon Fraser University
CityInSight	2019	Sustainability Solutions Group & whatif? Technologies Inc. [76]	Sustainability Solutions Group & whatif? Technologies Inc.	System dynamics integrated with urban land-use (bottom-up, capital stock turnover)	Regional and municipal	Sustainability Solutions Group, City of Toronto, City of Ottawa, City of Halifax
DICE	2013R	Nordhaus [77], Nordhaus & Sztorc [78]	William Nordhaus	Integrated assessment model	Global	Government of Canada
E3MC	2017	Systematic Solutions Inc. [79], Government of Canada [80]	Systematic Solutions, Inc. & Government of Canada	Hybrid (bottom-up, partial equilibrium)	National and sub-national	Government of Canada
EC-IAM	2014	Zhu & Ghosh [81] Manne & Richels [82]	Alan Manne, Robert Mendelsohn, Electric Power Research Institute, Government of Canada	Integrated assessment	Global with national and sub-national disaggregation	Government of Canada
EC-PRO	2016	Government of Canada [83]	Government of Canada	Top-down (general equilibrium)	National and sub-national, with the rest of the world	Government of Canada
ENERGY 2020	2017	Systematic Solutions Inc. [79]	Systematic Solutions Inc.	Bottom-up	Sub-national	Government of Canada
FUND	V3.6 (2012)	Anthoff & Tol [84]	Richard Tol, David Anthoff	Integrated assessment	Global	Government of Canada
GCAM	Version 5.3	Joint Global Change Research Institute [85]	Pacific Northwest National Laboratory	Integrated assessment (partial equilibrium)	Global with regional disaggregation	University of Alberta, Government of Canada
GEEM	2010	Peters et al. [86]	Navius Research	Top-down (general equilibrium)	National and sub-national	Navius Research
gTech	2017	Navius Research [11]	Navius Research	Hybrid (general equilibrium, bottum-up)	National and sub-national, with the rest of the world	Navius Research, Government of British Columbia and Alberta
LEAP	2016	Stockholm Environment Institute [87]	Stockholm Environment Institute	Bottom-up	Global, national, sub-national, regional, and municipal	New Brunswick; McPherson [88]
MEDEE	2016	Government of Quebec [89]	Transition énergétique Québec	Bottom-up	Sub-national	Government of Quebec
MESSAGE-MACRO	2018	McPherson et al. [90], Messner & Strubegger [91]	University of Victoria	Hybrid (bottom-up, partial equilibrium)	National and sub-national	McPherson et al. [90]
NATEM-Canada	2017	Vaillancourt et al. [3], International Energy Agency [92]	International Energy Agency	Hybrid (bottom-up)	National with sub-national disaggregation	HEC Montreal, ESMIA Consultants
MAPLE-C	2006	U.S. Energy Information Administration [93]	US Energy Information Administration	Hybrid (bottom-up, general equilibrium)	National	Government of Canada
PAGE	PAGE09	Hope [94]	Chris Hope	Integrated assessment	Global with national and multi-national regions	Government of Canada
SK CGE	2017	Liu et al. [95]	Government of Saskatchewan	Top-down (general equilibrium, static)	Sub-national	Government of Saskatchewan

methodological differences across the reviewed models, as per the search string criteria described in Section 3. In fact, hybrid approaches should be treated as a spectrum of methodological integrations of top-down and bottom-up attributes because most models start as either bottom-up or top-down continuing to evolve into hybrid methods.

The resulting models have diverse developers and users, which includes academics, government agencies, and private consultants. Rarely was a model developer the exclusive user of a model. The majority of models, both publicly available and those subject to private licensing agreements, were initially developed for a specific objective, then subsequently modified by users to explore a wide variety of topics.

The models returned by the search are also diverse in their analytical approaches, including three assuming a top-down general equilibrium approach (EC-PRO, GEEM, SK CGE), three taking a bottom-up approach (ENERGY 2020, LEAP, MEDEE), seven using hybrid approaches (CIMS, CIMS-Urban, E3MC, gTech, MESSAGE-MACRO, NATEM-Canada, and MAPLE-C), and three using system dynamics methods (Canada Energy Policy Simulator, CanESS, CityInSight). The remaining models (EC-IAM, DICE, PAGE, FUND, GCAM) are integrated assessment models [[96]]. Two models that used to inform municipal climate policy, CIMS-Urban, and CityInSight, include spatial representations in their methods, although by way of distinct analytical approaches.

Several sets of models are often used together. First, the E3MC model is composed of two separate sub-models—ENERGY 2020 (which is frequently used in isolation as well) and a macroeconomic model of the Canadian economy called The Informetrica Model [97]. Second, GEEM and CIMS have been used in combination but is increasingly being replaced by the gTech model. Third, the CIMS-Urban model uses a GIS based land-use sub-model to determine non-financial costs, while maintaining almost all of the other features of CIMS.

Table 2 evaluates the models against the four criteria and associated sub-criteria identified in Section 4.1 using studies found through the scoping review method (see search strings and inclusions criteria in Section 3).

4.2.1. Treatment of technology

4.2.1.1. Explicit representation. The majority of the models reviewed explicitly represent technologies to differing extents: NATEM-Canada, LEAP and CIMS explicitly represent thousands of technologies across all sectors, while EC-IAM, EC-PRO and Canada Energy Policy Simulator include tens of technologies, and E3MC, ENERGY 2020, GCAM, gTech, MEDEE, MESSAGE-MACRO, and MAPLE-C lay somewhere in between. Interestingly, technologies were not represented using exclusively bottom-up methodological approaches. For example, EC-PRO is a "top-down" general equilibrium model that represents about 20 technologies across all sectors of the economy. In contrast to the majority, other "top-down" models GEEM and SK CGE implicitly represent technologies through the calibration of sector production functions, as do the DICE, FUND, and PAGE integrated assessment models. Although Canada Energy Policy Simulator, CityInSight, and CanESS explicitly represent new or retrofit technologies, they implicitly represent base year capital stock composition, again through model calibration.

4.2.1.2. Technological change. The reviewed models were grouped in three categories in terms of how they represent technological change: exogenously, endogenously, or not represented. First, the Canada Energy Policy Simulator, CanESS, and CityInSight models represent technological change exogenously by user specification of penetration rates and declining capital costs for near-commercial technologies. EC-PRO exogenously specifies both declining capital and operating costs and economy-wide energy efficiency improvements. Similarly, GCAM and GEEM represent technological change via exogenously specified capital costs. DICE and FUND models take a slightly different approach by improving the efficiency of "carbon-saving technological change" (e.g., carbon capture and storage technologies), in addition to applying economy-wide efficiency gains through sector-specific production functions.

A second category of models represent technological change endogenously, primarily by way of declining capital costs for near-commercial technologies based on technology market shares from previous model years. This is the case for CIMS, CIMS-Urban, NATEM-Canada, E3MC, ENERGY 2020, EC-IAM, gTech, MESSAGE-MACRO, and MAPLE-C. In addition, some of these models also have the option to represent technological change using other methods, including: declining non-financial costs (CIMS, gTech), and clustering effects and increasing return feedbacks (MESSAGE-MACRO). Finally, LEAP, MEDEE, PAGE, and SK CGE do not represent technological change.

4.2.2. Microeconomic realism

4.2.2.1. Market heterogeneity. Several models explicitly represent market heterogeneity by including a parameter that determines, in part, how much market share a given technology captures based on its relative costs, including CIMS, CIMS-Urban, gTech, E3MC, ENERGY 2020. CIMS and gTech differ in that they draw on empirical studies of either observed market behavior or stated preferences in discrete choice surveys in order to estimate market heterogeneity in addition to non-financial decision factors (see subsequent section).

Another group, mostly made up of "top-down" full equilibrium models and integrated assessment models, represent market heterogeneity by calibrating their production functions to historical data (DICE, FUND, PAGE, MAPLE-C, SKE CGE), and/or to the outputs of "bottom-up" models (EC-PRO, GEEM). Three models represent market heterogeneity through a similar calibration routine in their "business-as-usual" scenarios, but do not in other policy scenarios—i.e., Canada Energy Policy Simulator, CanESS, CityInSight. Finally, EC-IAM does not represent market heterogeneity.

4.2.2.2. Non-financial decision factors. About half of the reviewed models explicitly represent non-financial decision factors, while the other half either do so implicitly or not at all. In the case of the former, the methods used were diverse. CIMS, CIMS-Urban, and gTech use intangible cost parameters and revealed discount rates, while E3MC and ENERGY 2020 use logistic functions in their calculation of energy service technology market shares. GCAM and MAPLE-C represent non-financial decision factors by way of a market share competition parameter, and MEDEE does the same for technology competition in heating systems. NATEM-CANADA uses technology specific discount rates.

In much the same way as the representation of market heterogeneity, the Canada Energy Policy Simulator, CanESS, and CityInSight models implicitly represent non-financial decision factors in their "business-as-usual" scenarios, but not in other policy scenarios. The three integrated assessment models (DICE, FUND, PAGE), in addition to MESSAGE-MACRO, and SKE CGE implicitly represent non-financial decision factors in all scenarios through calibration to historical data, while EC-PRO and GEEM implicitly represent this dynamic through calibration to "bottom-up" models (i.e., ENERGY 2020 and CIMS, respectively). EC-IAM does not represent non-financial decision factors.

4.2.3. Macroeconomic realism

4.2.3.1. Trade effects and finance. Most reviewed models in some way represent trade effects, but finance and monetary features are not often represented. However, documentation of the treatment of trade was generally less thorough in comparison to information required to assess models against other criteria.

In some cases, it was unclear if international or inter-provincial trade of energy or non-energy commodities is represented, and if so, how. This made it difficult to categorize models based on their approaches. The majority of reviewed models represent international trade of energy or non-energy commodities, but it is unclear how exactly it is accomplished (i.e., CanESS, CityInSight, E3MC, EC-PRO, GCAM, MAPLE-C, NATEM-Canada). Model documentation for several models such as CIMS, GEEM, gTech, and SK CGE made clear that they use an Armington [70] specification in their representation of trade, whereby goods and services are treated as non-perfect substitutes. The DICE and EC-IAM models do not represent trade, but instead treat regional outputs of commodities as perfect substitutes.

A number of models treat the modelled region (usually Canada) as a small open economy, meaning that the region is a "price-taker" on international import and export markets (i.e., CIMS, GEEM, gTech, MESSAGE-MACRO, EC-PRO). Notably, several models represent government fiscal balances, monetary flows, and exchange rates, using diverse methods (i.e., GEEM, E3MC, MAPLE-C). ENERGY 2020 and NATEM-Canada do not represent the role of finance in the energy-economy. There was insufficient information to determine whether fiscal and monetary dimensions were addressed for the remaining models.

4.2.3.2. Energy equilibrium. Model documentation provided high quality information about how models treat the supply-demand balance of energy within the economy; most represent energy equilibrium by way of price-quantity feedbacks for energy commodities (i.e., CIMS, CIMS-Urban, E3MC, EC-IAM, EC-PRO, GCAM, GEEM, gTech, LEAP, MESSAGE-MACRO, MAPLE-C, SK CGE). Four models partially represent an energy supply-demand balance using own price elasticities for energy commodities (i.e., Canada Energy Policy Simulator, CanESS,

Table 2
Energy-economy model inventory: Evaluation against assessment criteria.

	Treatment of technology		Microeconomic realism		Macroeconomic realism			Policy representation	
Model	Representation	Technological change	Market heterogeneity	Non-financial decision factors	Trade effects & finance	Energy equilibrium	Non-energy equilibrium	Policy interaction	Policy types
Guiding question (s)	*Are technologies represented explicitly or implicitly? If explicitly, how many are represented?*	*How does the model account for technological change?*	*How does the model account for market heterogeneity?*	*How does the model account for non-financial decision factors?*	*How is inter-regional and international trade treated? How are monetary and financial dimensions represented?*	*Are energy commodities supply-demand balanced through price-quantity adjustments?*	Are non-energy commodities supply-demand balanced through price-quantity adjustments?	How is policy interaction treated in the model? How does the model avoid double-counting emissions reductions?	How does the model represent the following policy types: carbon pricing, performance standards, prescriptive regulations, and government investments and subsidies?
CIMS	Explicitly represents several thousand technologies across all sectors.	Includes declining capital and non-financial costs for near-commercial technologies. No backstop technologies.	Explicitly represents market heterogeneity via technology market share competition parameter.	Represents non-financial decision factors via "intangible cost" parameter and revealed discount rate.	Employs Armington specification for energy and non-energy commodities. Modelled region assumed to be a small open economy with capital infinitely available at world market price.	Yes.	Partial, using own-price elasticities for non-energy commodities.	Policies are treated as constraints, either across entire economy, or for particular technologies or sectors. Constraints can become non-binding if more stringent policies are modelled.	Explicitly represents technology specific regulations, carbon tax, prescriptive regulations. Implicitly represents cap-and-trade and performance standards through carbon tax and proxy fuels.
Canada Energy Policy Simulator	Explicitly represents ~30 vehicle technologies and 8 electricity generation technologies. Implicitly represents base year capital stock composition through calibration.	Does not represent endogenous technological change. Declining capital costs are specified exogenously. Near-commercial technology market shares are specified by user.	Implicitly represented in business-as-usual (BAU) scenario. Not represented in other policy scenarios.	Implicitly represented in BAU scenario. Not represented in policy scenarios.	Not addressed in the literature.	Partial, via own-price elasticities for energy commodities.	Partial, via own-price elasticities for non-energy commodities.	Explicitly accounts for double counting of GHG reductions. Non-pricing policies are typically specified for individual sectors or technologies. Does not account for unintended cross-cutting policy interactions.	Explicitly represents carbon tax, revenue recycling, technology subsidies, prescriptive regulations. Implicitly represents cap-and-trade through carbon tax.
CanESS	Explicitly represents new or retrofit technologies as discrete processes. Implicitly represents base year capital stock composition through calibration.	No endogenous technological change. Penetration rates for near-commercial technologies are set exogenously.	Implicitly represented in BAU scenario through calibration. Not represented in other policy scenarios.	Implicitly represented in BAU scenario through calibration. Not represented in other policy scenarios.	Interprovincial and international trade included to equilibrate supply-demand of energy commodities and feedstocks.	Partial, via own-price elasticities for energy commodities.	No.	Not addressed in the literature.	Not addressed in the literature.
CIMS-Urban	Explicitly represents several thousand technologies across all sectors.	Includes declining capital costs for near-commercial technologies. Includes option for declining non-financial costs. No backstop technologies.	Explicitly represents market heterogeneity via technology market share competition parameter.	Represents non-financial decision factors via "intangible cost" parameter and revealed discount rate. Non-financial costs of personal mobility modes are calculated in land-use model.	Not addressed in the literature.	Yes.	Partial, using own-price elasticities for non-energy commodities.	Policies treated as constraints, either across entire economy, or for particular technologies or sectors. Constraints can become non-binding if more stringent policies are modelled.	Explicitly represents technology specific regulations, carbon tax, and prescriptive regulations. Implicitly represents cap-and-trade and performance standards through

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Renewable and Sustainable Energy Reviews 153 (2022) 111739

Table 2 (*continued*)

	Treatment of technology		Microeconomic realism		Macroeconomic realism			Policy representation	
Model	Representation	Technological change	Market heterogeneity	Non-financial decision factors	Trade effects & finance	Energy equilibrium	Non-energy equilibrium	Policy interaction	Policy types
									carbon tax and proxy fuels.
CityInSight	Explicitly represents new or retrofit technologies as discrete processes. Implicitly represents base year capital stock composition through calibration. More than 80 building archetypes, represented from city to individual building scale. Spatially explicit passenger transportation technologies.	No endogenous technological change. Penetration rates for near-commercial technologies are set exogenously.	Implicitly represented in BAU scenario through calibration. Not represented in other policy scenarios.	Implicitly represented in BAU scenario through calibration. Not represented in other policy scenarios.	Interprovincial and international trade is included to equilibrate supply-demand of energy commodities and feedstocks.	Partial, via own-price elasticities for energy commodities.	No.	Not addressed in the literature.	Not addressed in the literature.
DICE	No.	Technological change is exogenous and takes two forms: economy-wide technological change, and “carbon-saving” technological change.	Implicitly represented through calibration.	Implicitly represented through calibration.	No international trade, outputs of different countries treated as perfect substitutes.	No.	No.	Not addressed in the literature.	Policies represented by single "emissions control" parameter.
E3MC (ENERGY 2020 + TIM)	~100 across all sectors.	Declining capital costs using both exogenous and endogenous methods, which vary based on technology. No backstop technologies.	Explicitly represented via ENERGY 2020 technology market share parameter.	Represented through ENERGY 2020 logistic functions calibrated to historical data, and via TIM calibration.	Accounts for international trade of about 100 commodities. Represents government fiscal balances, monetary flows, and exchange rates. Does not equilibrate government budgets and investment or employment markets.	Yes.	Yes.	Controls for interaction by basing scenarios on incremental decision-making.	Explicitly represents cap-and-trade and performance standards via credit markets. Explicitly represents carbon tax, prescriptive regulations, and government subsidies.
EC-IAM	~20 technologies across electricity generation, liquid fuel supply, industry, and passenger transportation sectors.	Represented exogenously via autonomous energy efficiency improvement, and endogenously via declining capital costs for particular near-commercial technologies.	Not addressed in the literature.	Not addressed in the literature.	Internationally traded energy and non-energy commodities are treated as homogeneous. Monetary and finance dimensions not addressed in the literature.	Yes.	No.	Not addressed in the literature.	Not addressed in the literature.
EC-PRO	~20 technologies across all sectors.	Exogenously specified declining capital costs and operating costs, and energy efficiency improvements for particular near-	Implicitly represented through calibration (typically to ENERGY 2020 model).	Implicitly represented through calibration (typically to ENERGY 2020 model).	Canada assumed to be a price taker on international markets. Represents international trade from rest of word of energy and non-energy commodities.	Yes.	Yes.	Not addressed in the literature.	Explicitly represents cap-and-trade and performance standards via credit markets. Explicitly represents carbon tax, prescriptive

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Table 2 (*continued*)

Model	Treatment of technology: Representation	Treatment of technology: Technological change	Microeconomic realism: Market heterogeneity	Microeconomic realism: Non-financial decision factors	Macroeconomic realism: Trade effects & finance	Macroeconomic realism: Energy equilibrium	Macroeconomic realism: Non-energy equilibrium	Policy representation: Policy interaction	Policy representation: Policy types
		commercial technologies.			Provinces are linked through bilateral trade.				regulations, and government subsidies.
ENERGY 2020	~100 across all sectors.	Declining capital costs using both exogenous and endogenous methods, which vary based on technology. No backstop technologies.	Explicitly represented via technology market share parameter.	Represented through logistic functions calibrated to historical data.	Monetary policy not represented. Trade effects not addressed in the literature.	Yes. Energy supply-demand sectors solve for price-quantity equilibrium.	No. Static economic forecast remains constant.	Controls for interaction by basing scenarios on incremental decision-making.	Explicitly represents carbon tax, prescriptive regulations, and government subsidies. Implicitly represents cap-and-trade and performance standards through carbon tax.
FUND	No.	Exogenous energy-efficiency and carbon-efficiency improvements are specified in sectoral production functions.	Implicitly represented through calibration.	Implicitly represented through calibration.	Not addressed in the literature.	Not addressed in the literature.	Not addressed in the literature.	Not addressed in the literature.	All climate policies represented as a single carbon price parameter.
GCAM	~50 technologies across all sectors.	Ability to exogenously input declining capital costs for near-commercial technologies.	Explicitly represented via market share competition "choice indicator" parameter.	Explicitly represented via market share competition "cost penalty" parameter.	Tracks international trade of energy commodities.	Yes.	Yes.	Not addressed in the literature.	Explicitly represents carbon pricing and technology-specific regulations. Does not represent revenue recycling. Represents cap-and-trade and performance standards through quantity constraints and linked "emissions markets."
GEEM	No.	No backstop technologies. Exogenous technological change. Near-commercial technologies are represented implicitly through calibration (typically to CIMS model).	Implicitly represented through calibration (typically to CIMS model).	Implicitly represented through calibration (typically to CIMS model).	Canada treated as a small open economy, and is a price taker on international export and import markets. Trade occurs both between provinces and between Canada and other countries, following an Armington formulation.	Yes.	Yes.	Not addressed in the literature.	Does not represent technology-specific regulations. Explicitly represents carbon tax and partial revenue recycling. Performance standards and cap-and-trade represented via credit markets.
gTech	Explicitly represents ~200 technologies across all sectors.	Near-commercial technologies are subject to endogenous declining capital costs. No backstop technologies.	Explicitly represented via technology market share elasticity parameter.	Explicitly represented via revealed discount rates, and "non-financial" costs in technology choice algorithm.	Canada treated as a small open economy. Trade occurs both between provinces and internationally, following an Armington formulation. Represents government fiscal	Yes.	Yes.	Framework allows for examination of combinations of policies and associated interactions.	Represents carbon tax and revenue recycling. Explicitly represents performance standards and cap-and-trade via credit markets. Explicitly represents technology

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Table 2 (*continued*)

Model	Treatment of technology		Microeconomic realism		Macroeconomic realism			Policy representation	
	Representation	Technological change	Market heterogeneity	Non-financial decision factors	Trade effects & finance	Energy equilibrium	Non-energy equilibrium	Policy interaction	Policy types
					balances and monetary flows.				specific regulations and prescriptive regulations.
LEAP	Explicitly represents ~1000 technologies across all sectors.	No.	Not addressed in the literature.	Not addressed in the literature.	Not addressed in the literature.	Yes.	No.	Not addressed in the literature.	Not addressed in the literature.
MEDEE	Explicitly represents ~50 technologies across industry, buildings, and transportation sectors.	No.	Not addressed in the literature.	Represented via technology competition in new heating systems. Not addressed for other end-uses in the literature.	Not addressed in the literature.	No.	No.	Not addressed in the literature.	Does not represent technology-specific regulations or revenue recycling. Implicitly represents carbon pricing and performance standards.
MESSAGE-MACRO	Explicitly represents ~100 technologies.	Represented endogenously via declining costs, clustering effects and increasing return feedbacks for particular near-commercial technologies.	Implicitly, via macroeconomic model calibration.	Implicitly, via macroeconomic model calibration. Unclear in the literature if addressed via technology market share competition.	Global model represents trade flows of energy commodities. Capital investments are tracked. The effect of monetary policy is not addressed. Trade of non-energy commodities not addressed.	Yes.	Yes.	Full equilibrium credit markets allows for representation of unintended policy interactions.	Explicitly represents technology-specific regulations, other prescriptive regulations, carbon tax, and revenue recycling. Represents cap-and-trade and performance standards via credit markets.
NATEM-Canada	Explicitly represents 4500 technologies across all sectors.	Option to represent exogenously or endogenously via declining capital costs of individual or "clustered" technologies.	No.	Represented via technology-specific revealed discount rates.	Represents inter-provincial and international flows of energy commodities exogenously. Does not represent monetary policy.	Partial, via own-price elasticities for energy commodities.	No.	Not addressed in the literature.	Explicitly represents technology-specific regulations, other prescriptive regulations, carbon tax, and revenue recycling. Represents cap-and-trade and performance standards via credit markets.
MAPLE-C	Explicitly represents several hundred technologies across all sectors.	Represented endogenously via declining capital costs for most near-	Implicitly addressed via "equipment weight" parameter in	Represented via "equipment weight" parameter in market share competition.	Projects international energy commodity market conditions endogenously, given	Yes.	Yes.	Controls for interaction by basing scenarios on incremental decision-	Explicitly represents technology-specific regulations, other prescriptive

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Table 2 (*continued*)

Model	Treatment of technology		Microeconomic realism		Macroeconomic realism			Policy representation	
	Representation	Technological change	Market heterogeneity	Non-financial decision factors	Trade effects & finance	Energy equilibrium	Non-energy equilibrium	Policy interaction	Policy types
		commercial technologies.	market share competition.		exogenous rest-of-world supply curves. Represents monetary and finance dimensions.			making. Full equilibrium represents nintended policy interactions.	regulations, carbon tax, and revenue recycling. Represents cap-and-trade and performance standards via credit markets.
PAGE	No.	No.	Implicitly represented through abatement cost specification.	Implicitly represented through abatement cost specification.	Not addressed in the literature.	No.	No.	Not addressed in the literature.	Not addressed in the literature.
SK CGE	No.	No.	Implicitly represented through calibration.	Implicitly represented through calibration.	Trade occurs between Saskatchewan and other regions following an Armington formulation.	Yes.	Yes.	Not addressed in the literature.	Explicitly represents carbon tax. Other policy types not addressed in the literature.

CityInSight, NATEM-Canada), while MEDEE and PAGE do not represent energy equilibrium, but instead rely on exogenous energy supply assumptions.

4.2.3.3. Non-energy equilibrium. Less information was available about non-energy commodity equilibrium than for energy commodities. However, most of the general equilibrium models, by definition, use price-quantity adjustments to balance supply-demand (i.e., E3MC, EC-PRO, GCAM, GEEM, gTech, MESSAGE-MACRO, MAPLE-C, SK CGE). In addition, ENERGY 2020 also represents non-energy equilibrium, and the CIMS model uses own price elasticities to partially equilibrate supply and demand for non-energy commodities. Several models, which use “bottom-up” and system dynamics analytical approaches do not balance supply-demand of non energy commodities (i.e., ENERGY 2020, LEAP, MEDEE, NATEM-Canada, CanESS, CityInSight, Canada Energy Policy Simulator).

4.2.4. Policy representation

4.2.4.1. Interaction. Model documentation often did not address how policy interaction is taken into account, and thus the information required to assess models against the “policy interaction” criterion was not available. Therefore, generalizations were not made across models in terms of how policy interaction is treated, except the in the case of the models described below.

CIMS (which uses a “bottom-up” partial equilibrium framework) treats policies as constraints in an optimization solver. Policies can become non-binding if more stringent policies are introduced. However, due to its partial equilibrium approach, CIMS does not simulate potential macroeconomic interactions such as capital movements between regions given stringent climate policy [19]. MAPLE-C and gTech similarly represent policies as constraints, but apply a full equilibrium framework, which allows them to capture interactive effects in regard to, for example, capital movements between regions, government taxation, and transfers between governments [11]. Interestingly, the Canada Energy Policy Simulator model uses a method to explicitly avoid double counting GHG emissions reductions treating non-pricing policies (e.g., prescriptive regulations) as “additive” relative to cross-sector pricing policies (e.g., carbon pricing). This approach is unique among the models reviewed here.

Some model documentation suggests that policy interaction depends on modellers’ approaches, rather than the analytical frameworks of the models themselves. For example, E3MC, ENERGY 2020, and MAPLE-C model documentation suggest that modellers often control for interaction by basing scenarios on incremental decision-making.

4.2.4.2. Policy types. The way that models represent particular types of policies can be categorized based on their analytical approach. A group of models, mostly using “bottom-up” approaches, were found to explicitly represent technology-specific regulations, carbon taxes, and prescriptive regulations (i.e., CIMS/CIMS-Urban, Canada Energy Policy Simulator, ENERGY2020, E3MC). This group implicitly represents cap-and-trade forms of carbon pricing, and performance standards, largely through the use of carbon taxes applied to groups of sectors or technologies across the economy.

Conversely, a second group of models (EC-PRO, GCAM, gTech, MESSAGE-MACRO, NATEM-Canada, MAPLE-C) mostly using general equilibrium frameworks combined with a disaggregated representation of technologies, explicitly represents cap-and-trade and performance standards via credit markets. This second group of models also explicitly represents carbon taxes, prescriptive regulations, and technology-specific regulations (e.g., government subsidies for electric vehicles).

GEEM and SK CGE do not explicitly represent technology-specific regulations precisely because they do not explicitly represent technologies. However, both “top-down” models explicitly represent carbon taxes and associated revenue recycling. MEDEE does not represent technology-specific regulations, but does represent carbon pricing and performance standards. The DICE integrated assessment model aggregates the representation of all climate policies in its use of a single "emissions control" parameter, which limits global emissions. The FUND model takes almost an identical approach, by representing all climate policies as a single carbon price parameter.

5. Implications for climate policy modelling

The review has several implications important to consider in modelling GHG and economic impacts of climate policies. The implications do not determine which model is 'best' and do not prescribe for all models to meet the proposed qualities because model choice depends in part on the type of research and/or policy question posed, and excessive model complexity may lead to higher uncertainties in results. In addition, other model characteristics unaddressed in the review may influence modelling projections of climate policy, including policy baselines and calibrations [98,99], model harmonisations [100,101], treatment of uncertainty [15], inclusion of high-resolution representation of time and space [29,30,44], and frequency of model parameter updates (e.g., for technology costs).

First, models should explicitly represent energy-related technologies. This means that technologies that supply or demand energy services are disaggregated within a model. The explicit and detailed representation of technologies is desirable because (a) it allows for the representation of technological change dynamics; (b) it allows for technology-specific data to be used by the model, either directly as inputs or in model calibration; (c) it allows for tracking different vintages of technologies over time; and (d) it helps modelling technology-specific policies [29,35].

Second, models should aim to represent technological change dynamics (i.e., how capital stocks of technologies evolve within the economy). This is particularly important for representing near-commercial technologies, because their attributes are not captured by historical data, and may also change over time [34,54,55]. The reviewed models represent technological change using a diverse range of exogenous and endogenous methods, and there is no consensus on the 'best' method. Ideally, the method(s) should be tailored to fit specific policy questions. For instance, representing technological change in one sector using exogenously specified declining capitals costs might be a reasonable approach if a climate policy is to be implemented exclusively in another. However, exogenous technological change can be considered a limitation if, for instance, changes in carbon prices do not cause increased market shares of low-carbon technologies, as would be expected.

Third, in terms of representing how consumer and firms make energy-related investment decisions, models should aim to capture both market heterogeneity and non-financial costs because (a) not all decision-makers will make the same decision given the same circumstances surrounding an energy-related investment and (b) many non-financial factors can influence decisions involving energy service technologies, especially at the household level. Incorporating these model features improves the accuracy of climate policy evaluation because it allows for a more realistic representation of consumer and firm behavior, which in turn allows modellers to use technology acquisition data [34,37,38]. There are many ways that models can represent these dynamics, including the use of revealed discount rates to account for non-financial factors and the use of market share competition parameters to account for market heterogeneity and/or differences in non-financial costs.

Fourth, models that seek to assess the economic effects of climate policy accurately should include a representation of trade and finance because GHGs are heavily affected by economic activity. In addition, providing information on key economic indicators such as changes in activity, changes in interprovincial or international trade, and structural shifts (e.g., labour shifting from high to low carbon intensity sectors) is likely to be useful to policy-makers [19,47]. Models that took a general equilibrium analytical approach are best suited to represent these features.

Fifth, energy-economy models used to evaluate the effects of climate policy should aim to link energy supply-demand using price-quantity adjustments, such that equilibrium is achieved for each energy source across all sectors [30,71]. This provides a realistic representation of the interdependencies of energy systems, which is necessary to simulate stringent climate policy. A model that does not represent energy supply-demand is not able to capture dynamics that are central to climate policy analysis (e.g., changes in the composition of energy consumption given changing prices). However, it may be valid to represent energy equilibrium exogenously or endogenously, depending on the model's intended use.

Finally, models should aim to accurately represent different types of policies, and do so within an integrated framework that captures unintended policy interactions [30,41]. Different model attributes are important for modelling particular types of polices, on a case-by-case basis. Thus, modellers should understand precisely how a given model represents each policy, and how interactive effects of multiple policies are represented. Modellers may also find value in controlling for policy interaction by basing scenarios on incremental decision-making. The models that are well suited to represent a diverse range of policies, in addition to how those policies might interact, contained an explicit representation of energy-related technologies within a full equilibrium framework.

6. Conclusions

The narrative literature review identified four main modelling assessment criteria that influence the ability of energy-economy models to project GHG and economic impacts of climate policies: treatment of technology, microeconomic realism, macroeconomic realism, and policy representation. While these criteria can be considered generally well-known, the analysis relied on a narrative literature search of 3,982 publications to confirm that these criteria are in fact the most widely used as key characteristics important for producing 'realistic' GHG and economic projections under climate policy. The study identified 21 energy-economy models used across Canada in the last decade and assessed them against these criteria. The majority of the reviewed models explicitly represent technologies, albeit at different levels, but that models are quite methodologically diverse in their representation of technological change. On aggregate, models represent market heterogeneity using a variety of methods but those that share methodological approaches generally represent market heterogeneity similarly. Additionally, about half of the reviewed models explicitly represent non-financial decision factors using diverse methods, while the other half either do so implicitly or not at all. Most models represent trade effects in some way, but financial or monetary features were less represented. The large majority of reviewed models represent energy equilibrium by way of price-quantity feedbacks for energy commodities. In contrast, only about half of the models (the full-equilibrium models generally) represented a non-energy supply-demand balance. Model documentation did not often address how policy interaction is taken into account, and that the way in which models represent particular types of policies can generally be categorized based on their analytical approach.

The study has several limitations. The review identified models using only two databases, ScienceDirect and Google Scholar, in Canada in the last decade. Restricting the search to these databases, geography, timeframe, and the narrow energy-economy focused search strings meant that the review provides only a sample of possible models and their application to climate policy evaluation. For example, integrated assessment models not currently used in Canada, may have Canada represented as a separate region, having useful implications for climate policy modelling in Canada. Future studies could broaden the inclusion criteria in search strings to include all energy-economy models that can produce Canada-relevant results. The assessment of energy-economy models also relied in part on non-peer-reviewed 'grey' literature, the quality of which is uncertain. To increase transparency and trust in modelling methodologies, it is important to have publicly available databases of open data and open code models with methodological documentation, similar to some emerging databases of integrated assessment and systems dynamics models [102–104]. Finally, the study does not attempt to prescribe which near-commercial technologies should be included in energy-economy models, or document which technologies are actually represented in different models. However, this would be an important area of research, as the representation of particular technologies across models varies, and is crucial to evaluating economic and GHG outcomes.

Despite these limitations, the study suggests six considerations that can help researchers and policy-makers choose among energy-economy models and better assess impacts of climate policies. Specifically, models should explicitly represent energy-related technologies and technological change dynamics, capture both market heterogeneity and non-financial costs of technologies, include a representation of trade and finance, link energy supply-demand using price-quantity adjustments, and accurately represent different types of policies and policy interactions. While these model attributes receive widespread support in literature, they may also add some complexity and trade-offs important to consider relative to each particular policy and/or research question.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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